Increased damage from fires in logged forests during droughts caused by El Niño

F. Siegert*†, G. Ruecker‡, A. Hinrichs§ & A. A. Hoffmann‖

** Ludwig Maximilians University, Department of Biology, Luisenstrasse 14, 80333 München, Germany*
† Remote Sensing Solutions GmbH, Wörthstrasse 49, 81667 München, Germany
‡ ZEBRIS GIS and Consulting, Lipowskystrasse 26, 81373 München, Germany
§ Sustainable Forest Management Project (SFMP-GTZ-MoFEC), PO Box 1087, Samarinda 75123, Kalimantan Timur, Indonesia
‖ Integrated Forest Fire Management Project IFFM/GTZ, Pekantoran Dinas Kehutanan, Jln. Harmonika, Samarinda, 75001, Kalimantan Timur, Indonesia

In 1997–98, fires associated with an exceptional drought caused by the El Niño/Southern Oscillation (ENSO) devastated large areas of tropical rain forests worldwide. Evidence suggests that in tropical rainforest environments selective logging may lead to an increased susceptibility of forests to fire[1–4]. We investigated whether this was true in the Indonesian fires, the largest fire disaster ever observed[5,6]. We performed a multiscale analysis using coarse- and high-resolution optical and radar satellite imagery assisted by ground and aerial surveys to assess the extent of the fire-damaged area and the effect on vegetation in East Kalimantan on the island of Borneo. A total of 5.2 ± 0.3 million hectares including 2.6 million hectares of forest was burned with varying degrees of damage. Forest fires primarily affected recently logged forests; primary forests or those logged long ago were less affected. These results support the hypothesis of positive feedback between logging and fire occurrence[4]. The fires severely damaged the remaining forests and significantly increased the risk of recurrent fire disasters by leaving huge amounts of dead flammable wood.

During the last three decades pressure on forests by logging and massive transmigration has strongly increased on the island of Borneo[7]. According to official sources[8], more than 180 million cubic metres of large logs have been harvested from the forests of East Kalimantan since 1969. Fires were often started for large-scale forest conversion into plantations and land clearance for agriculture[6]. Fires also occurred because impoverished people used fire for hunting and for the collection of turtles from swamp forests and in disputes over land ownership[9]. At the end of the ENSO episode in the early spring of 1998 fires flared up in East Kalimantan, an area that was not much affected in 1997 (refs 6 and 10). Fires associated with extended ENSO-related droughts were described as early as 1914 for East Kalimantan but these were small in scale[3]. Undisturbed tropical rainforest is normally highly resistant to fire because of low loads of available fuel, low fuel-energy content and high humidity even during drought[11–13]. Fire became a threat to the rainforests in east Kalimantan only recently. Although the drought of 1971–72 did not result in significant fire damage, 3.5 million hectares of mainly forested land were destroyed during the 1982–83 ENSO, the largest fire disaster observed in tropical rainforests until then[14,15].

Fire occurrence in 1997–98 was monitored using coarse-resolution images from the advanced very-high-resolution radiometer (AVHRR, 1,100-m ground resolution) aboard the National Oceanic and Atmospheric Administration (NOAA) 12 and NOAA 14 satellites, which were processed to detect 'hot spots'. During a period of 290 days from August 1997 to May 1998 more than 65,000 hot spots were recorded in East Kalimantan. The time series of hot spots showed that the fires started in the Mahakam river basin, which had already been severely affected by the 1982–83 fires. Subsequently fires spread to other regions and propagated often as a fire front (red hot spots in Fig. 1a).

Assessment of fire impact requires satellite images with higher resolution than that of NOAA–AVHRR. Optical satellite systems were severely hampered during the fires by haze and rain following the drought. Therefore we used data acquired by the high-resolution active microwave instrument (AMI, 25-m ground resolution), a synthetic aperture radar (SAR) onboard the European Remote Sensing Satellite (ERS)-2 to locate and assess the extent of the burned area. Active microwave systems are able to penetrate clouds and haze. Difference detection techniques applied to pairs of ERS-2 SAR images allowed us to map the burned area with high accuracy and to assess the level of fire damage from changes in image intensity and texture[16]. The AMI instrument detects structural features of the earth's surface (volume scattering) and the moisture content of the vegetation (dielectric properties)[17]. Fire decreases both. Volume scattering decreases because fire consumes vegetation and moisture content decreases because fire-damaged plants lose their foliage. Furthermore, the opened canopy and the reduced leaf biomass allow more microwave backscatter from the exposed ground surface.

The total area affected by fire in East Kalimantan was 5.2 ± 0.3 million hectares (Fig. 1b). The radar analysis showed that 24% of the burned area had moderate fire damage (25–50% of trees dead), 42% had severe fire damage (50–80% of trees dead), and 34% showed total fire damage (>80% of vegetation killed). In this last category we distinguished two cases: (1) the vegetation was almost totally consumed by the fires (mostly grass and bush land); and (2) most of the standing biomass was not consumed but tree mortality was almost 100%. The latter case occurred mostly in pristine peat swamp forests (12% of the total burned area). To determine what type of vegetation was burned we produced a vegetation map differentiating six land-cover classes using ERS-2 radar images acquired in August 1997 just before the fires (Fig. 1c). The burned area was then intersected with this land-cover map (Table 1). The result shows that fire mainly affected lowland dipterocarp, secondary forests and peat swamp forests, whereas the vast majority of mangrove and highland dipterocarp forests in mountainous areas escaped the fires.

To investigate whether intensified use of forest increased fire susceptibility, all available planning data on pre-fire legal land status, such as natural forest concessions, plantations, industrial timber crops and protected forests, were collected from official sources, digitized and transferred into a geographical information system (GIS). The intersection of the radar-based fire-impact map with land-use status boundaries (Table 2) showed that the bulk of the burned area (5.2 million hectares) were timber concessions, plantations or land of undefined status (mostly agriculture, shifting cultivation and fallow land), while only 0.4 million hectares were protected (presumably pristine) forests. The highest damage occurred in pulp-wood plantations: almost two-thirds were destroyed by the fires (severe to total fire damage). Some 24% of the forest concession area (9.7 million hectares) in East

Table 1 Damaged area for different land covers

Land cover	Area (ha)	Burned (ha)	Burned (%)
Grassland (mainly *Imperata cylindrica*), low bushes	368,900	292,600	79.3
Lowland dipterocarp forest	5,379,600	2,177,900	40.5
Mangrove forest	1,042,100	91,700	8.8
Peat swamp forest	426,100	311,100	73.0
Secondary forest, plantation, farmland	2,283,400	1,723,400	75.5
Wetlands	358,700	290,400	81.0
Land cover not mapped by ERS (mainly highland dipterocarp forest)	3,882,600	330,800	8.5
Total	13,741,400	5,217,900	—

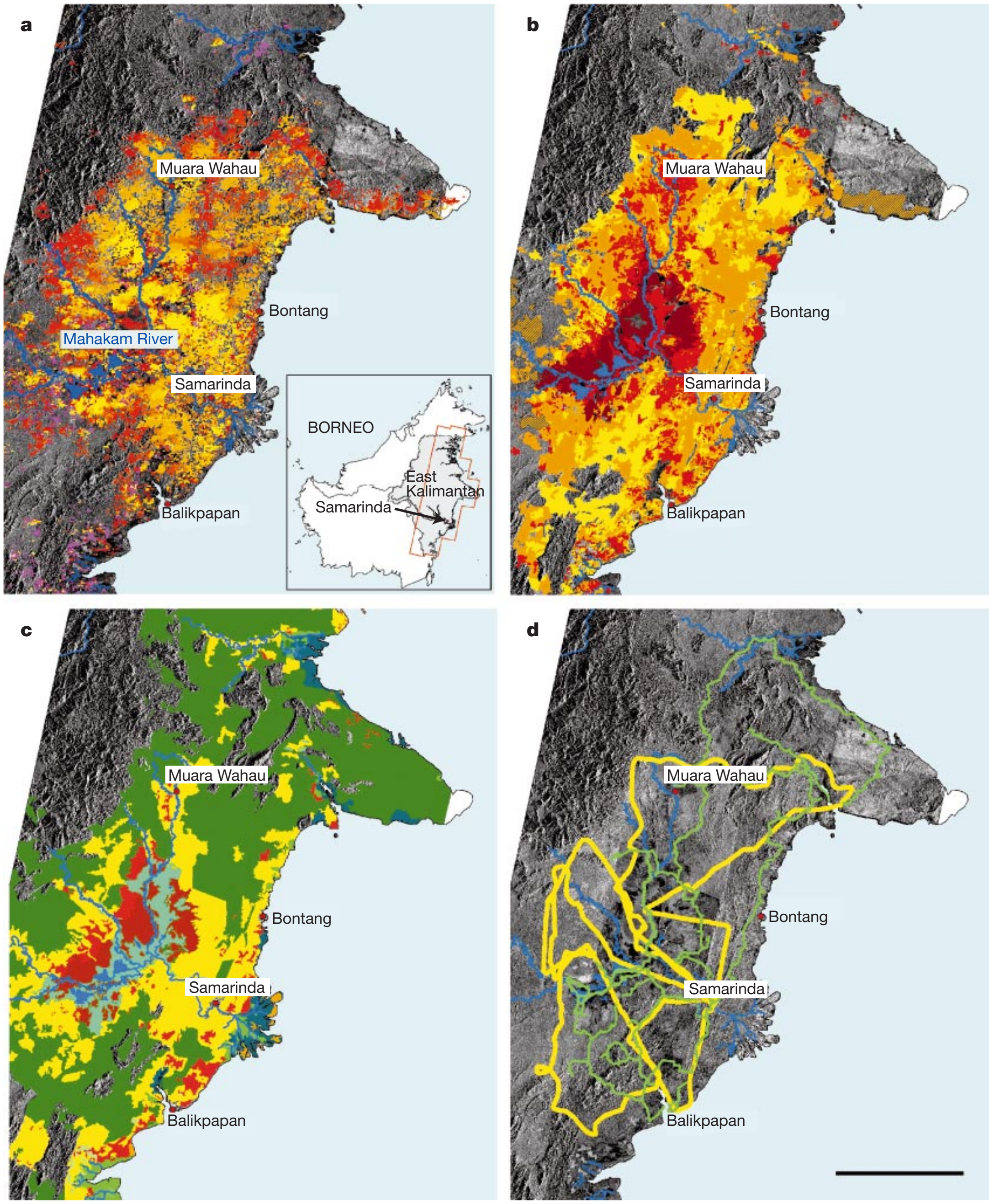

Figure 1 Fire occurrence and fire impact in 1997/98 in East Kalimantan, Borneo, Indonesia. Rivers are shown in blue. **a**, Time series of NOAA–AVHRR fire hot spots. Yellow–red colour gradient, January to April 1998; purple, August to November 1997. In 1998 the fires started in the densely populated Mahakam basin. Background is the ERS SAR mosaic, August 1997. Scale bar, 100 km. The inset shows a map of Borneo, East Kalimantan and the studied area (red outline). **b**, Fire scars and fire impact map. Damage levels are as follows: yellow, moderate; orange, severe; red, total damage of vegetation; brown, total damage of trees in peat swamp forests (see text). **c**, Pre-fire vegetation map derived from ERS SAR images. Green, pristine and logged dipterocarp forest; brown, peat swamp forest; light green, mangrove; yellow, degraded/secondary forests/plantations; red, grassland, bushland, clearings; and aqua, wetlands. No colouring, mountainous areas (mainly highland dipterocarp forest). **d**, GPS recorded aerial (yellow) and ground surveys (green).

Table 2 Damaged area for different land uses

				Damage (% of total burned area)		
Land status (1998)	Area (ha)	Burned (ha)	Burned (%)	Moderate	Severe	Total
Forest concessions	9,771,400	2,350,000	24.0	32.7	52.6	14.7
Pulpwood plantations	1,393,100	884,000	63.4	23.7	48.6	27.7
Oil palm plantations	746,600	382,500	51.2	21.9	51.8	26.3
Protected forests	4,562,000	440,100	9.6	19.1	59.9	21.0
Other land use (undefined & agriculture)	3,275,480	1,161,300	35.4	9.2	6.0	84.8
Total (whole province)	19,748,500	5,217,900	26.4	24	42	34

Plantations include established and planned concessions. For damage classes, see text.

Kalimantan was burned and more than half of this area showed severe damage.

As official land-use data may not fully reflect the actual condition of the forest just before the disaster, we used the only available, relatively cloud-free high-resolution (30 m) Landsat-5 Thematic Mapper (TM) images (covering about 15% of the ERS study area) as an additional source of information to identify logged and undisturbed forests. A historical and a recent land-cover map were produced from images acquired in 1990/92 and during the fires in February–March 1998. To investigate fire impacts on undisturbed and logged forests the TM land-cover map was intersected with the ERS–SAR fire impact map (total matching area 3,587,100 ha). Only 5.7% of undisturbed forests were affected by fire, compared to 59% of logged forest and 70.7% of the non-forest area (Fig. 2). Fire impact was also more severe in logged forests: 48% had severe or total damage, in contrast to only 4% of the undisturbed forests. Peat swamp forests were excluded from this analysis because logging did not occur and fire behaviour was different.

A detailed field survey of fire impact was conducted in a 100,000-ha forest concession. The concession management had not implemented any operational fire protection measures. Information about the standing volume of living and dead trees and the damage level was collected by surveying the entire concession area[18]. The degree of fire impact was strongly correlated with the time elapsed after logging (Fig. 3). In forest areas logged between 1996–98 the volume of dead trees was almost equal to the volume of living trees, while in forest areas logged between 1969–81 the volume of living trees was almost six times higher than that of dead trees. Damage levels showed the same pattern: in recently logged forests (1996–98) severe damage was found in 49.5% of the burned area compared to only 26.3% in old logged forests and 17.3% in pristine forest (data not shown). In pristine forests and forests logged long ago dead biomass consisted mainly of litter on the forest floor causing relatively weak surface fires (onsite observations). Where logging activity had occurred, logging waste and dense undergrowth of fast-growing pioneer species (trees less than 20 cm diameter at breast height, d.b.h.) provided huge fuel loads. Open forest canopy in logged forests also increases photon flux density resulting in increased flammability[19]. Fires were occasionally observed reaching into the crowns of older trees with hollow trunks.

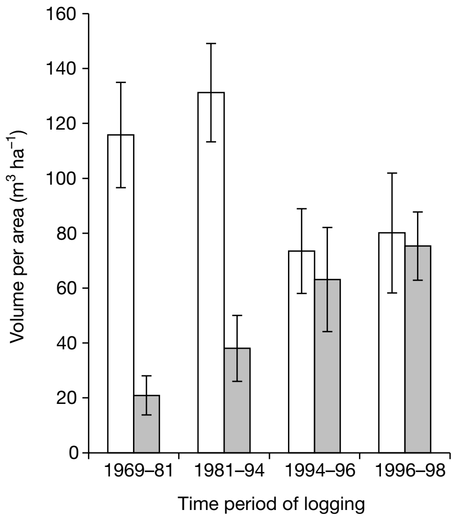

Figure 3 Fire impact measured as volume of living and dead trees in burned areas logged at different times in the past. White bars, living trees; grey bars, dead trees. The volume was measured for all trees over 20 cm d.b.h. (3,044 trees) on 306 sample plots. Error bars are 95% level of confidence for mean. Logged area (n = number of sample plots): in 1969–1980/81, 6,722 ha ($n = 62$); in 1981/82–1993/94, 5,464 ha ($n = 51$); in 1994/95–1995/96, 5,677 ha ($n = 55$); in 1996/97–1997/98, 7,579 ha ($n = 70$). Differences in percentage of dead tree volume were significant at the 0.05% level of confidence for plots logged between 1969 and 1994 and plots logged between 1994 and 1998 (one-way analysis of variance with posterior Scheffé test for group differences).

We used logging roads as an indicator of forest disturbance and prepared maps of the historical (before 1992) and recent network of logging roads (roads established between 1992 and 1998) from the TM images. Within the studied concession area we analysed fire impact (damage levels) within 1,000-m-wide strips centred on logging roads. Fire impact was much higher in proximity to recently established logging roads (65% of the area burned) compared to old logging roads (16% of the area burned) (Fig. 4).

The ground survey of one concession showed that fire destroyed

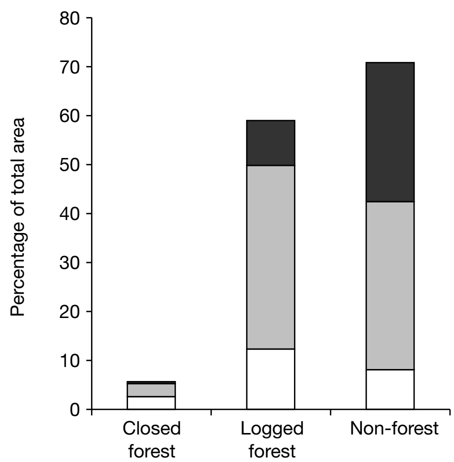

Figure 2 ERS SAR-derived fire damage for different land cover, derived from TM as a percentage of the total area of each land cover. White, moderate fire damage; grey, severe damage; black, total damage. The non-forest class includes *Imperata cylindrica* grasslands, forest mosaics, recently established plantations and agriculture, including fallow land.

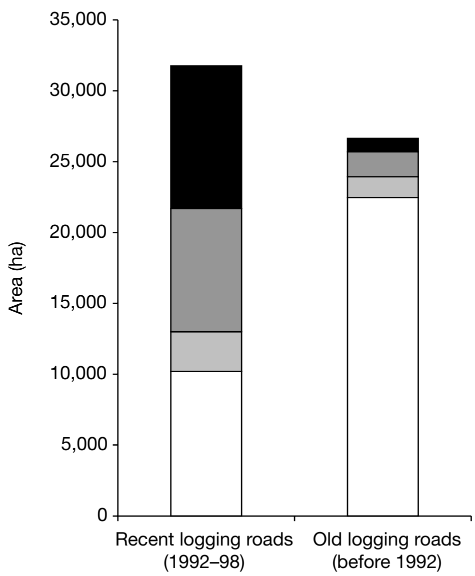

Figure 4 Fire impact within 1,000 m of logging roads. White, unburned; light grey, moderate fire damage; dark grey, severe damage; black, total damage.

an average 15 m^3 of merchantable timber per hectare in logged forests, which constitute the bulk of the burned forests. Assuming that a log volume value of 10 m^3 per hectare holds for all timber concessions affected by fire, we conservatively estimate economic losses of merchantable logs totalling more than 2 billion US dollars for the whole province of East Kalimantan (compare Table 2; the average market value of timber in Samarinda, the largest timber wholesale site, is 85 US dollars per cubic metre.

Many aspects of the 1998 fires in East Kalimantan closely resembled the fires associated with the 1982–83 ENSO event[14,15]. However, the 1997–98 fires by far surpassed the 1982–83 disaster and occurred in most of the areas damaged previously. The area affected by fire was 40% larger and fires predominantly spread into recently opened up (that is, logged) forests in that area.

Our results indicate that recently logged forests were hit harder by fire than undisturbed or partially recovered forests. These results support the hypothesis of positive feedback between logging and fire occurrence as has also been observed in the Amazon rainforests[4]. Thus selective logging directly contributed to the unprecedented extent of the 1998 fires. Many areas burned in 1982–83 fires suffered from recurrent fires in the 1990s and did not recover into fire-resistant tropical rainforest[3]. Similarly, for forested areas burned in 1998 the fire hazard has greatly increased, especially where fire left behind an opened-up forest or large volumes of unburned biomass as in peat swamp forests. Unless land-use policies are changed to control logging and to introduce reduced-impact logging techniques, recurrent fires will lead to a complete loss of Borneo's lowland rainforests[19–21]. □

Methods

Radar fire map

In all, 23 ERS-2 SAR precision images acquired in August 1997 represented the pre-fire vegetation status; 23 images acquired in July 1998 represented the post-fire situation. In addition one orbit (8 images) acquired during active burning in April 1998 was evaluated. pre- and post-fire images were co-registered to form bi-temporal image pairs consisting of the August–July and August–April orbits respectively. Co-registration was done automatically using the SAR Toolbox (ESA) with a registration error of less than one pixel. The images were calibrated to represent radar image backscatter, sub-sampled to 25-m pixel size, speckle-filtered, georeferenced (using orbital information and over 100 global positioning system (GPS) measured ground control points) and combined into a mosaic. The bi-temporal mosaic was visually interpreted onscreen using a Geographic Information System (scale 1:200,000, minimal mapping unit 100 ha). The interpretation of SAR signatures was based on GPS mapped ground observations made at 138 sites and evaluation of 42 video sequences scattered throughout the burned area along the tracks shown in Fig. 1d. Three different damage classes were defined on the basis of the estimated percentage of dead trees. NOAA–AVHRR hot-spot data served as an additional source of information during the interpretation process to reduce drought-related errors. An area was scored as 'burned' only when there was: (1) a clear decrease in backscatter or (2) a weak decrease in backscatter in conjunction with NOAA–AVHRR hot spots. Classification results were verified using more than 25 hours of GPS synchronized video material from four ground surveys and five aerial surveys conducted between April 1998 and September 1999 (Fig. 1d). The overall classification accuracy for the discrimination of burned from unburned surfaces was more than 95% based on 172 randomly selected digital video images from the aerial surveys. For discrimination of damage classes the error of commission was 10% and the error of omission was 30% for all classes. Most undetected areas belonged to damage class 25–50%. This, together with ground observations, suggests that low-intensity surface fires escape detection by both NOAA–AVHRR and ERS SAR.

Vegetation mapping

Landsat TM: Images were corrected for atmospheric moisture, georeferenced using a set of GPS measured ground control points and visually interpreted onscreen using a classification scheme based on ground observations (scale 1:100,000, minimal mapping unit 50 ha). ERS radar: The land-cover map was produced by visual interpretation of speckle-filtered, texture-enhanced artificial RGB (red–green–blue) images[22] (scale 1:200,000, minimal mapping unit 150 ha) with the following classes: lowland dipterocarp forest (pristine and logged), secondary forests including plantations and farmland, mangrove and peat swamp forests (generally pristine because the amount of merchantable timber is low), grass- and wetlands. The TM mosaic was co-registered onto the ERS mosaic using 50 ground control points (in flat areas) resulting in an accuracy of r.m.s. ±0.86 pixel (root mean square error, using a second-order polynomial transform). Overall agreement of the ERS and TM interpretation was 71% and 74% for forest/non-forest discrimination.

Ground survey in timber concession

The concession selected for the ground survey is a model forest area of the Ministry of Forestry (MoF), which is supported by the German government (technical support given by GTZ). The area was chosen because all activities before and during the fires are well documented and the MoF permitted us to conduct the survey in coordination with the concession management. The survey method of determining damage level and the standing volume of living and dead trees was a systematic line survey along 53 north–south oriented survey lines (spaced 1.2 km apart, 4–40 km long) covering the entire concession area (approximately 100,000 ha). Fire damage level (moderate, severe or total) was continuously estimated to the left and to the right side of each survey line and the average for each side separately recorded for 300-m sections. The average viewing distance from the survey lines into the forest was 60 m depending on topography and fire damage level. Every 900 m on every survey line a 20 m × 125 m sampling plot (0.25 ha) was established and all standing living and dead trees above 20 cm d.b.h. were measured and recorded. The forest inventory was performed from 18 June to 30 July 1998 and involved 12 teams consisting of five or six people each. The quality of data collection was evaluated on the basis of results from an independent check of 17 plots in the logged forests. The standard error of the standing tree volume was less than 5%.

Received 25 April; accepted 17 September 2001.

1. Nepstad, D. C. *et al.* Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* **398,** 505–508 (1999).
2. Uhl, C. & Buschbacher, R. A disturbing synergism between cattle ranch burning practices and selective tree harvesting in the eastern Amazon. *Biotropica* **17,** 265–268 (1985).
3. Goldammer, J. G., Seiber, B. & Schindele, W. in *Dipterocarp Forest Ecosystems: Towards Sustainable Management* (eds Schulte, A. & Schöne, D.) 155–185 (World Scientific, Singapore, 1996).
4. Cochrane, M. *et al.* Positive feedbacks in the fire dynamics of closed canopy tropical forests. *Science* **284,** 1832–1835 (1999).
5. ADB (Asian Development Bank)/BAPPENAS (National Development Planning Agency). *Causes, Extent, Impact and Costs of 1997/98 Fires and Drought.* Final Report, Annex 1 and 2. *Planning for Fire Prevention and Drought Management Project* (Asian Development Bank TA 2999-INO Fortech, Pusat Pengembangan Agribisnis, Margueles Pöyry, Jakarta, Indonesia, 1999).
6. Barber, C. V. & Schweithelm, J. *Trial by Fire* 5–10 (World Resources Institute, 2000).
7. Brookfield, H., Potter, L. & Byron, Y. in *Place of the Forest: Environmental and Socio-Economic Transformation in Borneo and the Easter Malay Peninsula* 158–178 (United Nations Univ. Press, Tokyo, 1995).
8. Forestry Statistic 1998/98 (Statistik Kehutanan) 27–28 (Provincial Forestry Department of East Kalimanton (Kantor Wilayah Kehutanan dan Perkebunan Propinisi Kalimantan Timur), Samarinda, Indonesia, 1999).
9. Colfer, C., Dennis, R. A. & Applegate, G. *The Underlying Causes and Impacts of Fires in South East Asia.* Site Report 8. Long Segar, East Kalimantan Province, Indonesia, 1–88 (Center for Internal Forestry Research, Bogor, Indonesia, 2000).
10. Siegert, F. & Hoffmann, A. A. The 1998 Forest Fires in East-Kalimantan (Indonesia): A quantitative evaluation using high resolution, multitemporal ERS-2 SAR Images and NOAA-AVHRR hot spot data. *Remote Sens. Environ.* **72,** 64–77 (2000).
11. Goldammer, J. G. (ed.) *Fire in the Tropical Biota. Ecosystem Processes and Global Challenges* Ecological Studies Vol. 84, 11–28 (Springer, Berlin, 1990).
12. Kauffmann, J. B., Uhl, C. & Cummings, D. L. Fires in the Venezuelan Amazon 1: Fuel biomass and fire chemistry in the evergreen rainforest of Venezuela. *Oikos* **53,** 167–175 (1988).
13. Cochrane, M. A. & Schulze, M. D. Fires as a recurrent event in tropical forests of the Eastern Amazon: Effects on forest structure, biomass, and species composition. *Biotropica* **31,** 2–16 (1999).
14. Malingreau, J. P., Stephens, G. & Fellows, L. Remote sensing of forest fires: Kalimantan and North Borneo in 1982–83. *Ambio* **14,** 314–321 (1985).
15. Leighton, M. & Wirawan, N. in *Tropical Rain Forests and the World Atmosphere* (ed. Prance, G. T.) 75–102 (AAAS Selected Symposium 101 Westview, Boulder, 1986).
16. Siegert, F. & Rücker, G. Use of multitemporal ERS-2 SAR images for identification of burned scars in south-east Asian tropical rain forest. *Int. J. Remote Sens.* **21,** 831–837 (2000).
17. Ulaby, F. T., Moore, R. K. & Fung, A. K. in *Microwave Remote Sensing: Active and Passive* Vol III *From Theory to Applications* 1811–1830 (Artech House, Dedham, 1986).
18. Solichin, S. H., Hinrichs, A., Soenoko, H. & Soemantri, H. *Burnt Forest Inventory* Sustainable Forest Management Project, SFMP Doc. No. 7b, 8–34 (Gesellschaft für Technische Zusammenarbeit—Sustainable Forest Management Project, Samarinda, Indonesia, 1999).
19. Holdsworth, A. R. & Uhl, C. Fire in Amazonian selectively logged rain forest and the potential for fire reduction. *Ecol. Appl.* **7,** 713–725 (1997).
20. Goldammer, J. G. Forest on fire. *Science* **284,** 1782–1783 (1999).
21. Jepson, P., Jarvie, J. K., MacKinnon, K. & Monk, K. A. The end for Indonesia's lowland rainforests? *Science* **292,** 859–861 (2001).
22. Siegert, F. & Kuntz, S. Monitoring of deforestation and land use in Indonesia with multitemporal ERS data. *Int. J. Remote Sens.* **20**(12), 2835–2853 (1999).

Acknowledgements

This research was funded by the German Federal Ministry of Economic Development and Cooperation and supported by the Gesellschaft für Technische Zusammenarbeit (GTZ) and the Indonesian Ministry of Forestry and Estate Crops, the European Space Agency (ERS European Remote Sensing Satellite *3.ERS* Announcement of Opportunities), the Joint Research Centre (Space Applications Institute) and the Global Fire Monitoring Centre (Max Planck Institute for Chemistry). We gratefully acknowledge helpful comments by C. N. David and P. T. L. Ganeca for co-operating with ground survey data collection and all staff members of the participating institutions.

Correspondence and requests for materials should be addressed to F.S. (e-mail: fsiegert@zi.biologie.uni-muenchen.de).